

## INTEGRATED GEOPHYSICAL APPROACH VIA JOINT INVERSION OF LONG-OFF-SET AND CENTRALLOOP TEM DATA: CASE STUDY FROM THE PEREKISHKUL, AZERBAIJAN

Avaz L. Mammadov, Ali G. Novruzov, Vagif G. Gadirov

Baku State University, 33, Z. Khalilov str. AZ 1148 Baku, Azerbaijan

DOI: <https://doi.org/10.30546/209805.2025.2.3.1005>

---

### Abstract

Mud volcanism is commonly observed in Azerbaijan and the surrounding South Caspian Basin. This natural phenomenon is very similar to magmatic volcanoes but differs in one considerable aspect: Magmatic volcanoes are generally the result of ascending molten rock within the Earth's crust, whereas mud volcanoes are characterized by expelling mixtures of water, mud, and gas. The majority of mud volcanoes have been observed on ocean floors or in deep sedimentary basins, such as those found in Azerbaijan. Furthermore, their occurrences in Azerbaijan are generally closely associated with hydrocarbon reservoirs and are therefore of immense economic and geological interest. The broadside long-offset transient electromagnetic method and the central-loop transient electromagnetic method were applied to study the inner structure of such mud volcanoes and to determine the depth of a resistive geological formation that is predicted to contain the majority of the hydrocarbon reservoirs in the survey area. One-dimensional joint inversion of central-loop and long-offset transient electromagnetic data was performed using the inversion schemes of Occam and Marquardt. By using the joint inversion models, a subsurface resistivity structure ranging from the surface to a depth of approximately 7 km was determined. Along a profile running perpendicular to the assumed strike direction, lateral resistivity variations could only be determined in the shallow depth range using the transient electromagnetic data. An attempt to resolve further two-dimensional/three-dimensional resistivity structures, representing possible mud migration paths at large depths using the long-offset transient electromagnetic data, failed. Moreover, the joint inversion models led to ambiguous results regarding the depth and resistivity of the hydrocarbon target formation due to poor resolution at great depths (> 5 km). Thus, 1D/2D modelling studies were subsequently performed to investigate the influence of the resistive terminating half-space on the measured long-offset transient electromagnetic data.

**Keywords:** Transient electromagnetic, Joint inversion, 1D/2D modelling/

---

\*Corresponding author.

E-mail address: [avez13@yahoo.com](mailto:avez13@yahoo.com) (Avaz L. Mammadov)

[ali.novruzov@hotmail.com](mailto:ali.novruzov@hotmail.com) (Ali G. Novruzov)

[vagif-geo@rambler.ru](mailto:vagif-geo@rambler.ru) (Vagif G. Gadirov)

### **Introduction:**

Mud volcanism is a commonly observed natural phenomenon in Azerbaijan and the surrounding South Caspian Basin (SCB). According to Planke et al. (2003), over 400 active mud volcanoes have been observed within the SCB, making it the region with the highest mud volcano density in the world (Feyzullayev, Kadirov, and Aliyev 2005). Worldwide, Milkov (2000) estimates the total number of known and inferred mud volcanoes to be  $10^3 - 10^5$ , most of which are located in deep sea regions.

Generally, mud volcanoes differ in size, appearance, eruption intensity, and eruption characteristics (Bohrmann, Kopf, and Spiess 2006; Milkov 2000, 2005; Feyzullayev et al. 2005). Some appear as truncated cones rising several hundred metres above the background landscape; others are rather flat and consist of large pools. Similar to magmatic volcanoes, the appearance of mud volcanoes largely depends on eruption frequency and the characteristics of discharge. Generally, mud volcanoes are categorised into three groups based on their eruption characteristics, each group being named after a particular individual (Judab 2005a):

**Lokbatan type:** Eruptions are sudden but infrequent but explosive. Expelled methane gas may self-ignite, causing a high flame above the crater.

**Chikishlyar type:** The activity is generally continuous and gentle; explosive eruptions do not occur.

**Shugin type:** The mass discharge is characterised by continuous activity that is interrupted by brief eruptive phases.

In recent years, mud volcanoes in Azerbaijan have attained growing economic interest as their occurrences are associated with hydrocarbon reservoirs (Bohrmann et al. 2006). As a consequence, the inner structure of mud volcanoes, related to both basin structure and hydrocarbon reservoir occurrence, has been explored quite frequently in recent years (e.g.: Abrams and Narimanov (1997), Stewart and Davies (2006), and Bonini et al. (2013)). However, most of the information is solely based on seismic or geologic data. A subsurface resistivity model of a mud volcano up to a depth of 7 km is, according to our knowledge, non-existent.

Few attempts have been made to derive shallow fluid migration paths of mud volcanoes in Azerbaijan utilising the direct current resistivity method (Scholte 2005). Moreover, several electromagnetic (EM) applications have been performed worldwide studying different mud volcano occurrences (Chow, Chang, and Yu 2006, Ellis et al. 2008; Istadi et al. 2009; Lin and Jeng 2010). A novel offshore transient controlled source EM system consisting of two transmitter polarisations has recently been applied to investigate a sea-floor mud volcano in the Mediterranean Sea (Swidinsky, Hölz, and Jegen 2013).

Within the framework of the ELMUD project (“Electromagnetic methods to study the inner structure of mud volcanoes in Perekishkul, Azerbaijan”) conducted by the Institute for Geophysics and Meteorology at the University of Cologne (IGM Cologne) between 2010 and 2012, the radiomagnetotelluric (RMT), central-loop transient EM (TEM), and long-offset transient EM (l.o.TEM) methods were applied in Azerbaijan to study the inner structures of mud volcanoes on various investigation scales. Although the RMT method has been previously used to image small-scale resistivity variations at shallow depths in the vicinity of the investigated mud volcanoes (not shown in this publication), the general resistivity models between TEM and RMT did not differ significantly for depths smaller than 10 m. Therefore, the following investigation is confined only to the joint interpretation of TEM and l.o.TEM.

The study aims at resolving both shallow and deep fluid migration paths presumed to cause two-dimensional (2D)/three-dimensional (3D) resistivity structures. Furthermore, the application of the l.o.TEM method aims to determine the depth of a resistive target formation, which, according to Abrams and Narimanov (1997) contains the majority of hydrocarbon reservoirs in the region. In order to reach the required investigation depth of at least 4 km, uncommon acquisition times of up to 15 seconds were applied during the LOTEM measurements. This novelty in acquisition was primarily necessary due to the very low resistivities within the survey area that are comparable to the resistivities found within in the marine environment.

#### APPLIED ELECTROMAGNETIC METHODS

TEM is an active EM method used to resolve the shallow electrical resistivity distribution of the subsurface (Ward and Hohmann 1988; Nabighian and Macnae 1991). A schematic field setup of the central-loop configuration is displayed in Fig. 1(a). A direct current flows through a horizontal loop that is assembled on the surface of the Earth. By abruptly interrupting the current signal, EM eddy currents are generated in the subsurface that diffuse in a form corresponding to the smoke ring process (Nabighian and Macnae 1991). These currents induce a further secondary magnetic field that can be measured as induced voltage by a horizontal receiver coil located at the center of the transmitter loop. The transient behaviour of the measured signal is thereby directly related to the subsurface resistivity distribution.

In Azerbaijan, a  $50 \times 50 \text{ m}^2$  transmitter loop and a  $20 \times 20 \text{ m}^2$  receiver loop were used. The induced voltage was measured in the time range from  $0.7 \mu\text{s}$  to 2 ms with a transmitter current amplitude of 1.5 A and from  $40 \mu\text{s}$  to 6 ms with a transmitter current amplitude of 9.5 A corresponding to the NanoTEM and ZeroTEM modes of the Zonge transmitter-receiver system, respectively. The TEM measurements were carried out with the NT-20 transmitter and the GDP-32II receiver from Zonge Engineering.

The LOTEM method has previously been applied in hydrocarbon and geothermal exploration (Kaufman and Keller 1983), coal exploration (Stephan, Schönenbrgifting, and Strack 1991), volcanic research (Müller, Hördt, and Neubauer 2002), and groundwater research (Lippert et al. 2012). A schematic LOTEM field setup of the broadside configuration applied in Azerbaijan is displayed in Fig. 1(b). For this setting, the receivers are installed alongside the transmitter at a distance referred to as the offset.

A square-wave current signal (Fig. 1(c)) with an amplitude of 30–35 A and a period of 24 seconds or 30 seconds was injected using the GÜT-30 transmitter (Zonge Engineering) over a dipole with a length of 750 m and 850 m. At an offset of 4–8 km the electric and magnetic receivers (SUMMIT-US and KMS820 acquisition units) were positioned. The potential difference caused by the horizontal electric field component in the x-direction was measured by an electric dipole using non-polarisable electrodes (see Fig. 1(d)). The vertical magnetic field component was obtained by measuring the induced voltage of a 40 m × 40 m × 54 winding receiver coil. It should be mentioned that, for LOTEM soundings, the direction of the transmitter dipole is generally defined as the x-direction.

The TEM and LOTEM methods have been applied jointly in numerous cases by the IGM Cologne to solve various geophysical problems (Scholl 2005; Lange 2003). The advantage of jointly applying the TEM and LOTEM methods is that a resistivity model can be determined corresponding to a depth range that is not resolved by the individual interpretation of each method. Thereby, the TEM transients determine the shallow resistivity structures, whereas the LOTEM transients resolve the deeper lying resistivity structures.

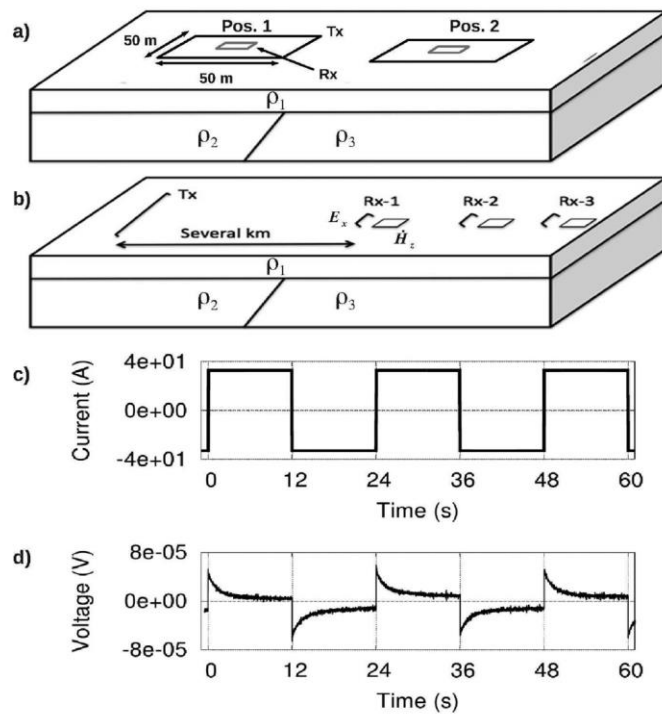


Figure 1 Schematic sketch of the central-loop TEM (a) and the LOTEM Broadside (b) field setup applied in this survey. For LOTEM, the  $E_x$  and  $H_z$  components were measured. Additionally, the LOTEM current signal (c) and LOTEM  $E_x$  receiver signal (d) are displayed for a current signal of 35 A and a period of 24 seconds.

## SURVEY AREA

The field surveys were conducted in the Azeri region of Perekishkul, located approximately 45 km northwest of the capital city Baku (Fig. 2(a)). The survey area marks the northwestern boundary of the SCB commonly referred to as the Kura Basin. This sedimentary basin is bounded to the north by the Greater Caucasus mountains and is of particular interest due to the vast occurrences of clastic–volcanogenic sedimentary rocks.

In general, the SCB is one of the deepest sedimentary basins in the world, consisting of a more than 20-km-thick sedimentary fill ranging from Mesozoic to Cenozoic (Brunet et al. 2002). A large portion of the sedimentary deposition occurred in a short Pliocene–Quaternary interval where the sedimentation rate within the SCB was of a factor five times higher compared with similar basins around the world (Clerc et al. 1996). The resulting excessive fluid pressure within the basin, in combination with tectonic overpressure, density inversion, and gas-hydrate dissociation, is the key factor leading to the formation of mud volcanoes in the region (Bohrmann et al. 2006; Milkov 2000, 2005; Feyzullayev et al. 2005).

Consequently, mud volcanism is a commonly found natural phenomenon in Azerbaijan. Approximately 300 of the 2000 mud volcano observations in the world were made in Azerbaijan (Judd 2005b). Until present, the deep subsurface resistivity structure of these individual volcanoes has not been investigated. Seismic data have been obtained at large mud volcanoes (e.g. Stewart and Davies 2006; Bonini et al. 2013) but is not available for the investigated survey area. However, based on these results, it is presumed that the mud origin layer may lie as deep as 14 km (Planke et al. 2003). As it rises to the surface, the mud passes through several different geological horizons and picks up different

materials (Scholte 2005)...Also, due to the common occurrence with hydrocarbon fields, mud volcanoes may often provide important channels for petroleum migration (Planke et al. 2003). The occurrences of hydrocarbon reservoirs are therefore often assumed based on the composition of the expelled mud volcano breccia, which consists of a mixed semi-liquid clay mass with various lithology of solid rocks derived from different age stratigraphic horizons that occur at various depths (Aliyev, Guliyev, and Rahmanov 2009). The expelled mud may also contain traces of oil or, in some cases, may pour out a lot of oil, e.g., at the Uchqute mud volcano (Aliyev et al. 2009). Generally, the mud rises along fault structures or in the form of a mud plume resulting in 2D/3D resistivity structures. The application of the LOTEM method aims to detect these deeply-lying resistivity variations.

The EM survey investigated three different mud volcanoes named Volcano 1, Volcano 2, and Volcano 3, distributed along a line running northwest to southeast within the survey area (Fig. 2(b)). The assumption that these mud volcanoes are likely to be connected by some sort of 2D/3D resistivity structure, i.e., fault structure or mud plume, seems quite reasonable. Unfortunately, due to the high logistical expenditure, only Volcano 3 was investigated using the LOTEM method, whereas all three mud volcanoes were investigated using TEM. The following interpretation will therefore focus only on Volcano 3. It is the southernmost of the three mud volcanoes, located approximately 1 km south of the highway (see Fig. 2(b)). Figure 3 shows the crater field of the investigated volcano, which consists of several micro formations (vents) that recurrently release mud, gas, water, and traces of oil.

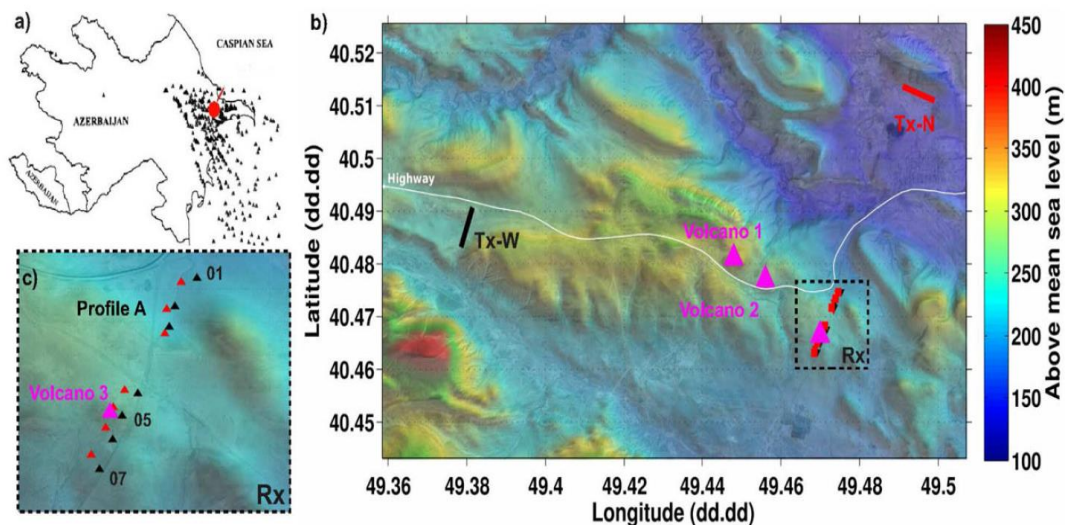


Figure 2 (a) The distribution of observed mud volcanoes onshore and offshore Azerbaijan and the location of the survey area marked by a red dot (modified after Feyzullayev et al. (2005)). (b) Topographic overlay map of the survey area, transmitter/receiver location, and position of the three mud volcanoes. The colour scale expresses the topographic data above mean sea level obtained from Jarvis *et al.*, 2008. The LOTEM transmitter and receiver locations shown in (c) are colour coded, i.e. corresponding transmitter and receiver locations have the same colour. The TEM stations are not displayed in this image but are consistent with the corresponding LOTEM stations. The map is from GoogleEarth.

Figure 2 displays the field setup applied during the LOTEM field survey. In total, thousands of time series were recorded at 14 stations along Profile A displayed in Fig. 2(c) by the red and black triangles. The profile extends from northeast to southwest, directly crossing Volcano 3 at station 05. In total, Profile A consists of 7 Ex and 7 Hz receiver stations measured from both the northern (Tx-N)

and western (Tx-W) transmitter positions. In Fig. 2, only the receivers are colour coded with their corresponding transmitter. The locations of the TEM stations are not explicitly shown but are generally consistent with the LOTEM receiver stations.

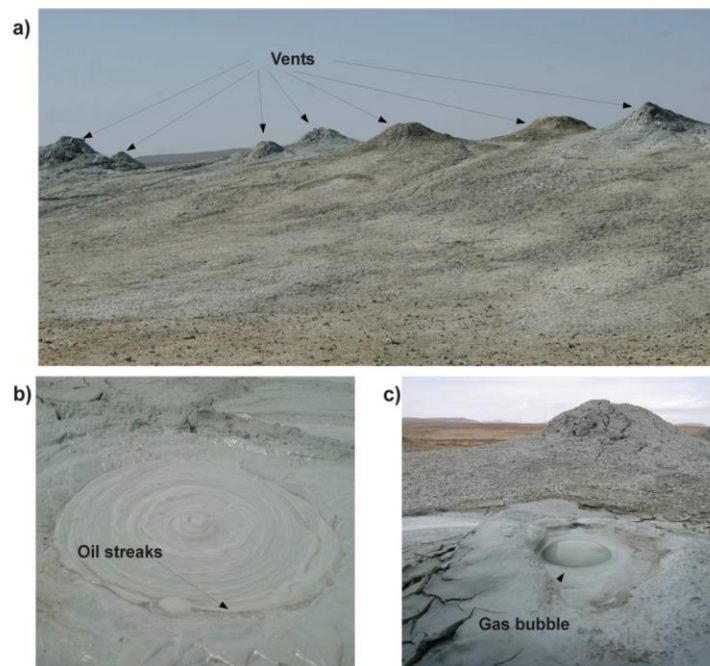


Figure 3 Pictures of the investigated mud volcano in Perekishkul, Azerbaijan. The mud volcano consists of several vents (a). Oil streaks (b) and gas (c) can be observed within the expelled mud breccia.

The perpendicular transmitter positions, one in the north and the other in the west, were chosen to investigate a possible 2D/3D resistivity structure, i.e., fault structure, mud plume, etc. within the study area. The goal is to analyse possible differences in the resulting inversion models obtained at one station from the two perpendicular transmitter positions. A strong discrepancy would indicate a 2D or even 3D resistivity distribution within the study area. In contrast, identical or fairly similar models would rather imply that the subsurface resistivity distribution varies only with the depth.

It should be mentioned that a second profile consisting of 4 Ex and 4 Hz receiver stations was measured approximately 400 m to the west of the mud volcano. The resulting inversion models are consistent with those obtained in Profile A. Therefore, the results of the second profile are not considered in this publication.

#### DATA PROCESSING

Measured EM time series are often contaminated by EM noise and consequently suffer from poor signal-to-noise ratios. Periodic noise generally contributes the main portion. A familiar cause is the local power network (50 Hz and harmonics). Additionally, sporadic noise sources may often appear in form of white noise, spikes, steps or drifts. It is crucial that the measured time series are processed prior to inversion to avoid misinterpreting the data.

The processing steps generally depend on the acquisition characteristics of the devices and, as a result, differ between the applied EM methods. In the following, the different processing steps of TEM and LOTEM are summarised.

#### Data Processing: TEM

The processing steps of the acquired TEM data sets largely depend on the measurement procedure. In the applied case, two NanoTEM transients (high and low gain) and one ZeroTEM transient were measured at each station. Each NanoTEM transient was obtained by a stacking algorithm that used 20 blocks consisting of 1024 measurements. For the ZeroTEM mode, 20 blocks consisting of 512 measurements were stacked. The goal of the data processing is to incorporate all the obtained data in the subsequent interpretation.

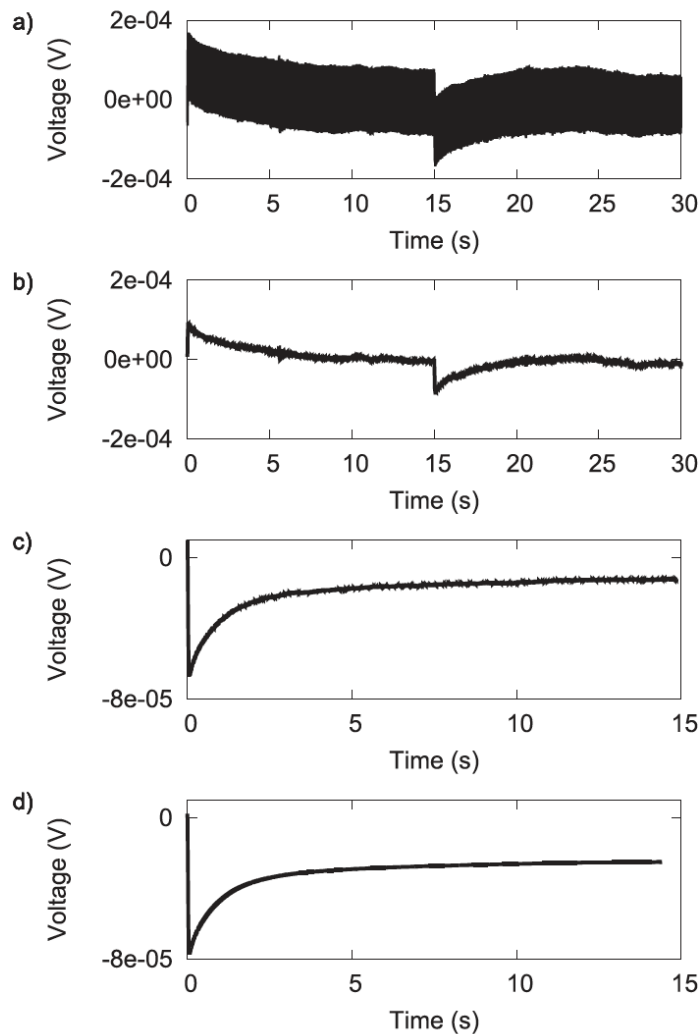
At this point, different strategies may be applied to handle the obtained transients. Theoretically, a joint inversion of all transients should lead to a sufficient result. However, to minimise the required computational effort, we propose to merge the NanoTEM and ZeroTEM transients to one, ideally ranging from 0.7  $\mu\text{s}$  to 6 ms (Fig. 4). Before this can occur, the non-zero transmitter turn-off time (3.5  $\mu\text{s}$  for NanoTEM and 55  $\mu\text{s}$  for ZeroTEM) is removed from each transient by approximating the turn-off time as a linear ramp and by applying a deconvolution algorithm (Fitterman and Anderson 1987; Helwig, Lange, and Hanstein 2003). Subsequently, the transients are merged and overlapping time points are eliminated.

#### Data Processing: LOTEM

The receiver devices utilised for LOTEM data acquisition do not have an internal processing/stacking algorithm. Data processing is performed subsequent to the measurement.

Generally, the high amplitude and uniformity of the periodic noise cause the most evident contamination of the measured LOTEM signal. Typically, the periodic 50-Hz frequency and its harmonics caused by the local power network were the greatest disturbance in the measured Azerbaijan data. As demonstrated in Fig. 5(b), these periodic distortions are removed from the measured time series by applying digital filtering techniques (Hanstein 1996). The applied filters are based on the assumption that a known periodic noise frequency can be reproduced using Fourier series and subsequently subtracted from the time series. Amplitude and frequency fluctuations of the periodic noise signal are considered by filtering in predefined segments.

After filtering, the resulting time series still contain a certain number of current switches, depending on the acquisition unit (e.g., two current switches at 0 seconds and 15 seconds in Fig. 5(b)). Ultimately, the goal is to obtain one transient (one current switch-on signal). Thus, each filtered time series is cut into the number of contained current switches and processed accordingly to multiply the total number of time series for later stacking purposes. Specific acquisition characteristics of the devices require a pre-trigger (also called onset) of 128 data points. Therefore, the cut is made 128 data points before each current switch, and consequently, each transient is reduced by the length ( $dt$ ) depending on the sampling rate ( $dt = 128 \cdot \text{sampling rate}$ ). The time series are mirrored at the x-axis and shifted along the time axis so that all time series have identical polarisation and the current switch begins at 0 seconds. Subsequently, all time series are levelled to the onset ( $t < 0$  seconds) to simulate a switch-on current signal and selectively stacked (Fig. 5(c)) to remove sporadic noise distortions. A time-variable Hanning window (low-pass filter) is additionally applied to the resulting transients to remove the remaining noise (Fig. 5(d)).



**Figure 4.** Chronological illustration of the LOTEM processing steps from the measured time series (a) to the processed transient (d). The raw time series (a) are superimposed by the periodic noise frequencies of 50 Hz and harmonics. These are filtered between steps a) and b) using digital filtering techniques. Subsequently, the time series are cut 128 data points before the current switch (located at 0 s and 15 s), shifted, levelled, and selectively stacked (c). Finally, the transient is smoothed with a time-variable Hanning window (d) and levelled to the onset.

Unfortunately, these standard processing steps could not be applied to the measured Hz transients. Additional noise sources, presumably caused by receiver coil motion due to strong winds during the measurements, prevented an interpretation of these transients. They could not be processed sufficiently using the above-mentioned steps. As a consequence, the following interpretation is solely based on the measured Ex transients.

#### **Conclusion:**

A joint interpretation of measured TEM and LOTEM data was performed to investigate the subsurface resistivity distribution of a mud volcano in the Perekishkul region of Azerbaijan.

The subsurface within the study area is generally characterised by relatively low resistivities ranging between 1 m and 10 m. These low resistivities were somewhat problematic and forced long LOTEM recording times. This unconventional time range of the recorded time series of up to 15 s is a novelty. Previous LOTEM measurements performed by the University of Cologne were limited to time-series lengths of only several seconds. The applied TEM method was highly effective in resolving the shallow resistivity structure of up to approximately 130 m. Due to the high resistivity contrast between the resistive overburden and the conductive mud volcano of approximately 10:1, the lateral extent of the mud volcano could be easily distinguished. In contrast, at large depths, the applied LOTEM method was not able to determine potential fluid migration paths due to the low resistivity contrast to the surrounding media. This does not coincide with the original presumption that the occurrence of mud volcanism is linked to 2D/3D resistivity structures, i.e., a fault or a mud plume. However, this conclusion has to be treated with caution since additional factors are likely to have influenced the results of the LOTEM measurements.

#### **References:**

- [1] Kaufman A.A. and Keller G.V. 2013. Frequency and Transients Soundings.
- [2] Constable S.C., Parker R.L. and Constable C.G. 2017. Occam's Inversion. [6] Marquardt D.W. 2015. An Algorithm for Least-Squares Estimation
- [3] Menke W. 2006. Geophysical Data Analysis: Discrete Inverse Theory.
- [4] Strack K.M. 1992. Exploration with Deep Transient Electromagnetics.
- [5] Ward S. and Hohmann D.L.B. 2018. Electromagnetic Theory for Geophysical Applications.
- [6] Nabighian M.N. and Macnae J.C. 2019. Electromagnetic Methods in Applied Geophysics.
- [7] Hördt A. and Scholl C. 2020. The Effect of Local Distortions on Time-Domain Electromagnetic Measurements.
- [8] Fitterman D.V. and Anderson W.L. 1987. Effect of Transmitter Turn-Off Time on Transient Soundings.